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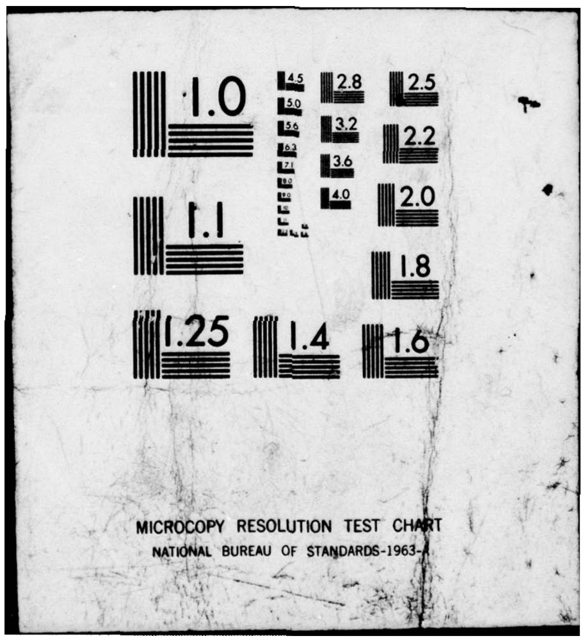
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SEA BASED AIRCRAFT

HABITABILITY CRITERIA

Contract N00600-76-C-1606
for the David W. Taylor
Naval Ship Research and Development Center

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This report defines sea based aircraft habitability criteria including vertical, lateral (horizontal) and roll limits for on-water operation. Heating, ventilation, air conditioning, illumination and volume limits are also indicated. Representative aircraft on-water motions are indicated and compared to motion sickness limits. No serious habitability limitations were uncovered for the surface following sea based aircraft concept. This report is a supplemental report to Rockwell International Report NR76H-137 "On-Water Motion Relationships Study" Final Report dated 15 January 1977.

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This report defines sea based aircraft habitability criteria including vertical, lateral (horizontal) and roll limits for on-water operation. Heating, ventilation, air conditioning, illumination and volume limits are also indicated. Representative aircraft on-water motions are indicated and compared to motion sickness limits. No serious habitability limitations were uncovered for the surface following sea based aircraft concept.

This effort was performed under Contract N00600-76-C-1606, dated August 17, 1976 (Rockwell International Sales Order, S.O. 2395) to the David W. Taylor Naval Ship Research and Development Center, Bethesda, Md., 20084.

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SEA BASED AIRCRAFT HABITABILITY CRITERIA

1.0 INTRODUCTION AND OVERVIEW

1.1 Introduction

This report investigates the surface following aircraft concept and defines habitability criteria including vertical and lateral motion limits, human comfort zones of temperature, and ventilation. The surface following aircraft concept is where the aircraft rides on the ocean surface supported by internal fuselage or float buoyancy much as a fishing boat or ship. With near vertical or extreme STOL takeoff and landing capabilities, touchdown loads are minimized and are no more than in flight design loads. Low speed control provides a very high sea state landing and takeoff capability to match the on water surface following high sea state capability.

The primary questions addressed in this report are (1) "What are the human limits of motion, comfort and volume for a surface following aircraft?" and (2) "What questions need to be answered to quantify these limits?"

1.2 Overview

This report is provided in response to the Human Limits Definition task of Contract N00600-76-C-1606, dated August 17, 1976 to the David W. Taylor Naval Ship Research and Development Center for a "Surface Loiter Aircraft On-Water Motion Relationships Study". This task involved the collection and review of available literature on human motion limits and sea sickness data. Discussions with Navy and industry human factors personnel were held.

Recommendations for subsequent efforts to define human tasks and performance levels are provided.

2.0 GENERAL BACKGROUND

The surface following concept is not new. Today's large fishing fleets and numerous small boats are all examples of the concept. Man can operate in these craft on the surface of the water and adequately perform varied manual operations. Sea sickness (kinetosis or mal de mer) is handled by the experienced sailor and usually affects the plebe or the occasional passenger. Sea based aircraft can offer similar motion characteristics as these small fishing vessels. With the application of outboard floats for roll stability, protection of the crew from wind, waves and rain and proper ventilation, heating and air conditioning, sea based aircraft offer the Navy a new approach to solving today's missions. Sea based V/STOL aircraft offer high airborne speeds (typically 400 knots) and high sea state operations with long endurance on the surface capabilities. The capability of this type of aircraft is described in Reference 1.

Remembering today's vast fishing fleet, the polynesian outriggers of the past, the Kon Tiki, and RA I and II, all of which survived the worst the seas had to offer, assures one that there are vessel characteristics of length, beam, weight, and stability that allow long duration, high sea state operation. The fact that humans can live and operate for very long periods on the sea is well established. The problem is one of determining compatible vessel characteristics. There may also be selection, training and adaptation that, for the polynesians, took place over centuries, that is needed to obtain the best crews for sea based aircraft. Reference to the Kon Tiki indicates that while the mission was a complete success (the expedition covered 4300 nautical miles from Peru to Tahiti in 101 days), the inexperienced crew suffered through an initial difficult period of sea sickness in the first weeks in the Humboldt current off the coast of Peru (Reference 2). The human limits for sea based operation are (1) one of type, amplitude, frequency and duration of input (primarily motion input) which varies with sea state, (2) amplifications or attenuation of this input as a result of the on-water characteristics of the aircraft and the human body, and (3) sensitivity of the human brain and organs to the resultant input. The human limits may be expressed in terms of physical damage, performance degradation, comfort regions and perception levels. Since the human is involved, the regions are often highly variable and subjective. Reference 3 addresses the problem of establishing human limits to vibration. Because of its significance, portions of Reference 3 have been included in Appendix A, Biodynamic Effects (body movement reactions to vibration inputs) and Appendix B, Subjective Vibration (Motion) Tolerance Levels.

Summarizing Reference 3:

1. Whole body resonant frequency, either seated or standing, for vertical g's is in the range of 4 to 6 Hz.* Note that sea state encounter frequencies at sea states 4 to 7 are .2 to .1 Hz. Transmissibility at these low frequencies is unity for all parts of the body and particularly for the head and shoulders.

2. Helmet restraints are not recommended for operation at resonant frequencies. No head restraints are considered necessary at low sea state frequencies (Author).

3. Human motion tolerance levels are highly subjective because of (a) interpersonal variability, (b) intra-personal variability, (c) situation specificity and (d) semantics (see Appendix B). Depending on the frequency, there can be an order of magnitude difference in subjective tolerance level. The very low frequency range (around 1 Hz) has a high variability both in degree and slope of the tolerance level (see Appendix B, Figure B-1).

4. Considering combined motions, below 4 Hz, comfort is lower for the gx (fore and aft) and gy (side to side) axis than for the gz (vertical) axis. Generalizing from sinusoidal limits to random vibration is not appropriate and gz limits cannot be used for other axes. To do so could result in overly conservative design limits not desirable for system design.

To answer the questions of Section 1, the following are needed: (1) specify that complete nature of the sea motion as translated through the vehicle, (2)specify the human transmissibility at these frequencies and types of motion (sinusoidal or random and single frequency or broadband), and (3) establish human tolerance limits. Methods are required to establish the sensitivity, level of training and adaptability of the subjects tested or subjects needed to meet the indicated motions.

*Lateral motion resonance occurs at about 1.5 Hz.

3.0 TOLERANCE LIMITS

This section indicates human tolerance limits for (1) vertical and horizontal vibration, (2) motion sickness and (3) heating, ventilation and air conditioning. A comparison to representative sea state motions for a Type A (40,000 Lb. TOGW) sea based aircraft is also provided (see Section 3.4).

3.1 Vertical Vibration Limits

Vertical vibration limits for fatigue-decreased proficiency (FDP)* are shown in Figures 1 and 2 (Reference 3). These same limits are presented in References 4, 5 and 6. As per Reference 4 ... "the specified limits of exposure for vibrations transmitted from solid surfaces to the body are in the 1.0 Hz to 80 Hz frequency range. The limits recommended are based on data available from both practical experience and laboratory experimentation in the field of human response to mechanical vibration. To date, useful observations have been made mainly in the frequency range between about 1 Hz and 100 Hz. The frequency range, its subdivisions, and the corner frequencies defined in this Design Note, have been selected in accordance with ANSI S1.6-1967 (1971) and with national standards in several countries. Vibrations in the frequency range below about 1 Hz are a special problem. These vibrations have symptoms such as kinetosis (motion sickness) which are different from those of higher frequency vibrations. The appearance of such symptoms depends on complicated individual factors not simply related to the intensity, frequency, or duration of the provocative motion. Mechanical vibrations applied to the feet or seat above the range of these limits produce sensations and effects which are increasingly dependent upon local factors such as the precise direction, site and area of application of the vibration to the body, and the presence of damping materials (e.g., clothing, footwear) which may control the vibratory response of the skin and superficial layers of the body. For these reasons, it is not possible (on the basis of present data) to formulate valid recommendations for frequencies outside the 1 Hz to 80 Hz band. The limits specified herein may be applied, within the specified frequency range, to periodic vibrations and to random or nonperiodic vibrations with a distributed frequency spectrum. Provisionally, it may also be applied to continuous shock-type excitation so long as the energy in question is contained within the 1 Hz to 80 Hz band."

The limits given here apply to vibration at the point of entry into the human body itself (i.e., at the body surface but not at the substructure of a resilient seat which may transform the vibration en route to the man).

*For military applications, Dr. Hanning von Gierke recommended the use of maximum safe exposure limits 6 db (or 2 times) above the FDP. Also, when subjected to vibratory stress, laboratory subjects performance improves with time (discussions with Mr. Peter Payne). The FDP and reduced comfort boundaries apply to transport and use near industrial machinery.

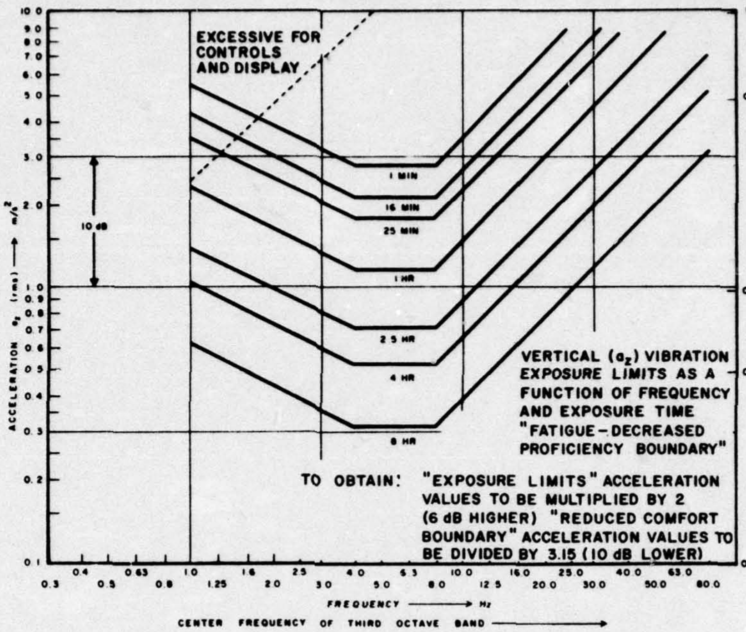

Figure 1. Vertical Vibration Limits - Acceleration Vs. Frequency

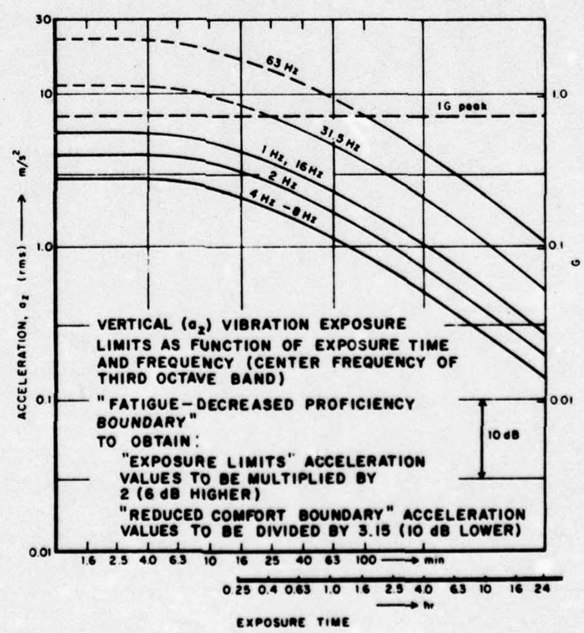

Figure 2. Vertical Vibration Limits - Acceleration Vs. Exposure Time

There are four physical factors of primary importance in determining the human response to vibration, namely, the intensity, the frequency, the direction, and the duration (exposure time) of the vibration. In the practical evaluation of any vibration where a physical description can be given in terms of these factors, three main human criteria can be distinguished. These are:

a. The preservation of working efficiency.

b. The preservation of health or safety.

c. The preservation of comfort.

Other factors being equal, somewhat higher levels of vibration are acceptable when health or safety is the criterion, in comparison with the limits appropriate to working efficiency. Conversely, lower limits are set when the criterion is the preservation of comfort. Military limits are considered to be 2 times or 6 db higher than the FDP levels shown.

It should be remembered that the vibration limits expressed are for continuous sinusoidal vibration. Broad band vibration limits such as wave motion, would be less restrictive. (Reference discussions with Dr. J. O'Hanlon).

3.2 Horizontal Vibration Limits

Figures 3 and 4 present horizontal vibration limits for fatigue-decreased proficiency (FDP). The limits apply to the x and y axes and are more restrictive at the lower frequency than for the vertical axis. The discussion of Section 3.1 also applies here.

3.3 Motion Sickness Limits

At frequencies below 1 Hz, human tolerance limits become one of establishing boundaries for avoidance of motion sickness conditions that cause a significant performance disablement. Motion sickness is any form of sickness (usually pallor, perspiration, nausea or vomiting) caused by sensory inputs (vestibular, visual or proprioceptive) that are abnormal for the human (See Section 3.8).

Based on studies of sea sickness and motion sickness (See Section 5.0 Definitions and Reference 7), vomiting was selected as the cardinal sign of motion sickness even though this may be a temporary condition. It is recognized that there are various degrees of motion sickness all of which degrade performance. Since frank vomiting interrupts task activity and was found to be a consistent indicator of motion sickness, it was used to specify motion sickness levels (see Reference 7).

There is a strong psychogenic factor in motion sickness where one person seeing another sick becomes sick himself. This is especially true in naive subjects being tested to the degree of frank vomiting.

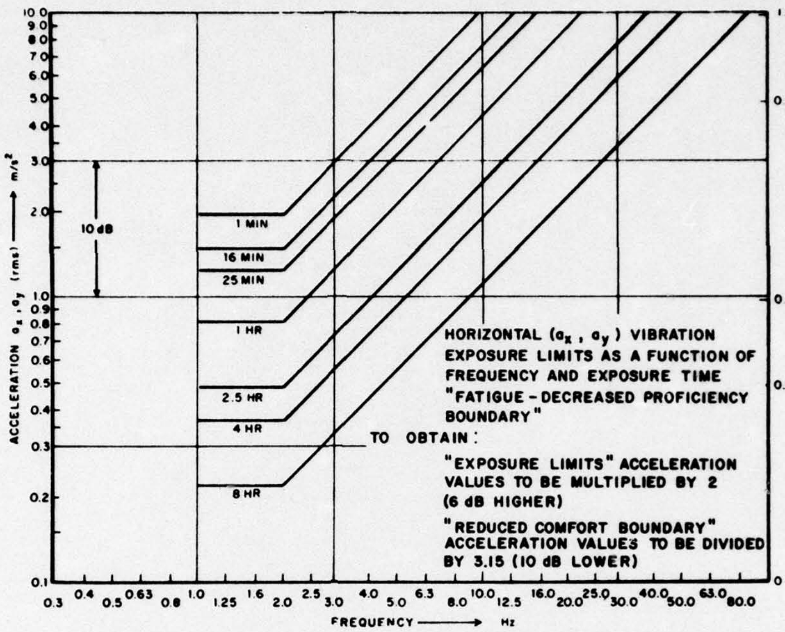

Figure 3. Horizontal Vibration Limits - Acceleration Vs. Frequency

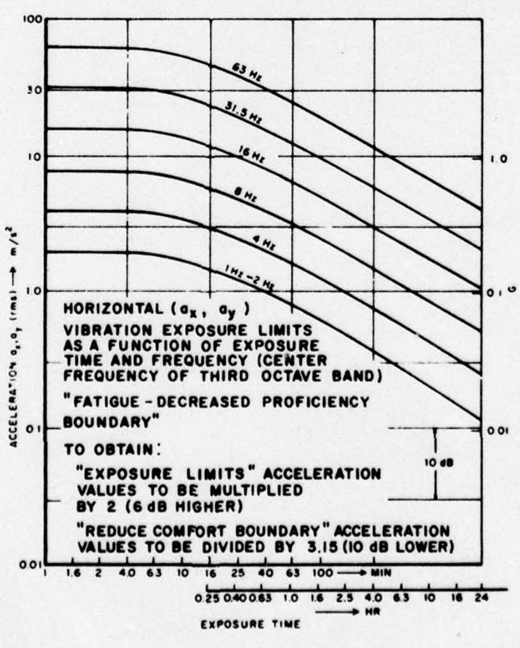

Figure 4. Horizontal Vibration Limits - Acceleration Vs. Exposure Time

Temporary motion sickness (i.e., vomiting) occurs at a much lower acceleration than does fatigue degraded performance and when it occurs, it severely degrades any performance capability. After this initial sickness, the operator may be able to adjust and still perform his mission.

Simple motion sickness (in terms of initial vomiting only) was studied in Reference 7 with limits established based on the cardinal sign of motion sickness (i.e., vomiting).* These limits are expressed in Figures 5, 6, and 7. The data was developed using untrained, unadapted subjects in a motion generator capable of vertical displacements of 20 feet. The accelerations were vertical and sinusoidal only. These results must be considered tentative since the effects of other variables have not been quantified. Some of these other variables are adaption/habituation, complex waveforms, cross-coupled linear and angular motion, extended exposure duration, body orientation, visual horizon and head movement (Reference 7).

Tests were conducted using narrow band frequency vibration only (hence the center frequency of one third octave band). This frequency band method is not representative of broad band sea spectrum energy and results in lower limits of MSI (author).

The data in Figures 5, 6, and 7 indicate a maximum MSI sensitivity at about .18 Hz. Studies by Dr. Ralph Stone indicate a most bothersome frequency range of .25 to .35 Hz.

Had sailors been tested (along with a means to go "topside" for a visual horizon reference and a breath of fresh air, for example) significantly lower motion sickness would have been observed. The incidence of sea sickness for a first passage across the ocean is very high compared to that of say the fourth passage. The study results indicated this as motion sickness tended to level out (see Figure 7) and after the first two hours, no increase in incidence occurred. For long duration missions (2 to 6 hours and over) it may be possible to tolerate a very low level of initial (temporary) sickness.

3.4 Representative Sea State Motions - Limits Comparison

Sea waves are not exactly sinusoidal in pattern. Reference 8 states that ..."waves are quite high at some places but quite low at other places in the same record" and "high waves follow low waves in a completely random and mixed-up way." "Individual waves are shaped like mountains with sharp angular tops. Crests are short, heights are not regular and crests are not all lined up in the same direction." Thus, sea wave action is not purely sinusoidal. This is important since most vibration and motion testing employs sinusoidal motion and waves are considered to be sine waves. The only way to describe waves at a given sea state is through the use of a

* Performance decrements prior to sickness were not found (on a consistent basis) and performance after vomiting was not measured.

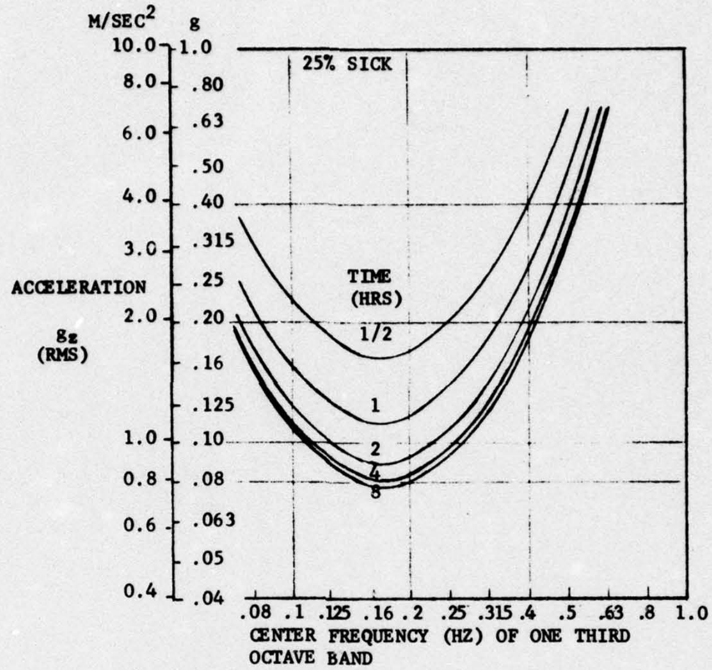

Figure 5. Twenty-five Percent Motion Sickness Incidence Condition - Unadapted/Untrained Subjects

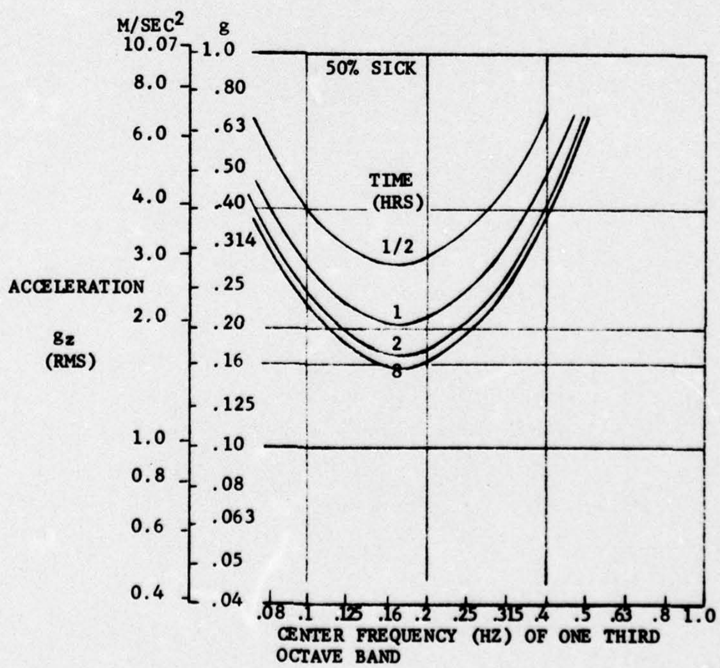

Figure 6. Fifty Percent Motion Sickness Incidence Condition - Unadapted/Untrained Subjects

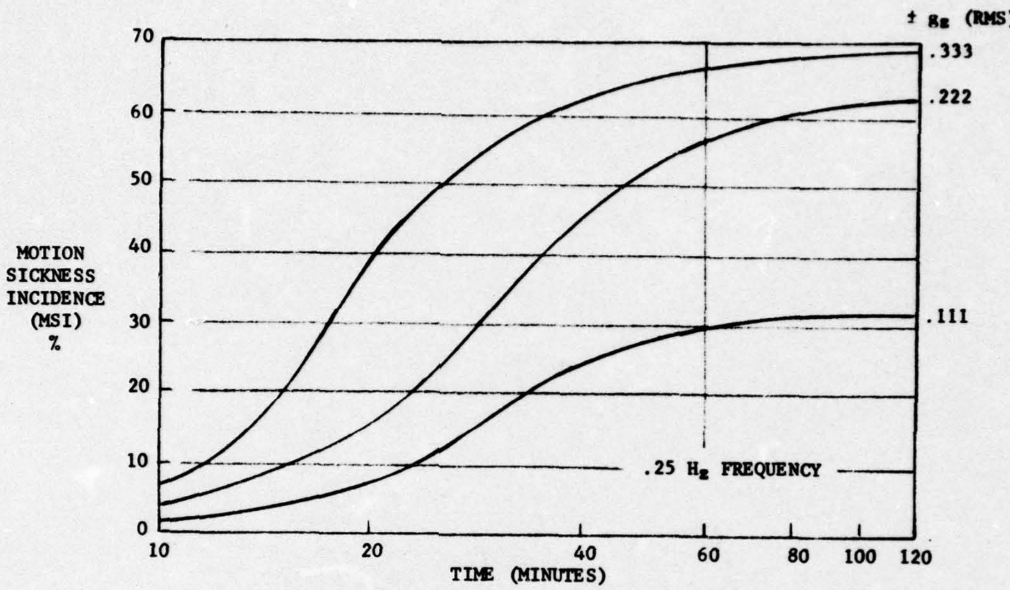

Figure 7. Motion Sickness Incidence Vs Time

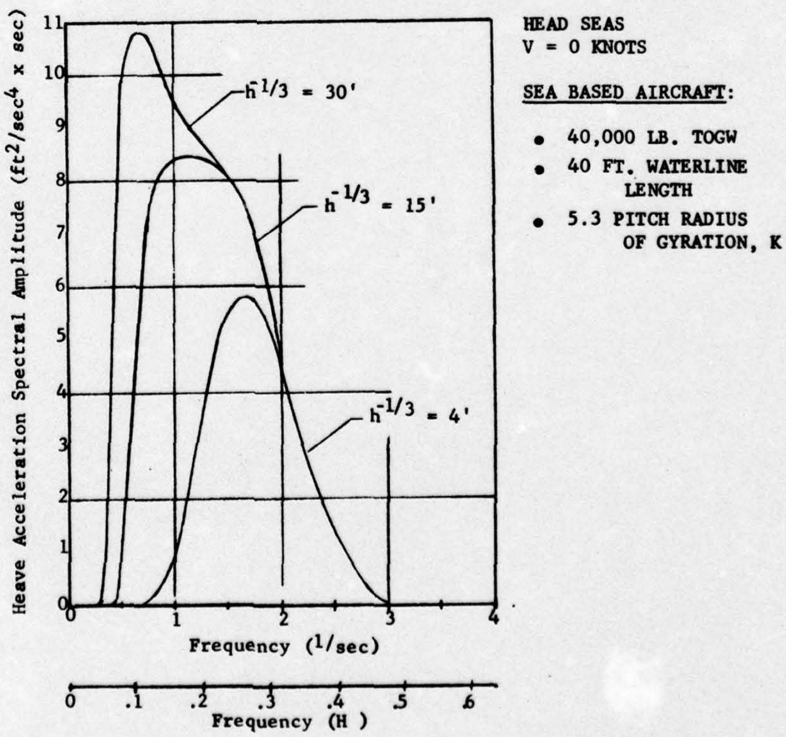

Figure 8. Spectral Density of the Vertical Acceleration at the Cockpit (13.8' Forward of) of the Single Hull Wing-Tail Sea Based Aircraft.

wave length, a wave period and a wave speed when in fact there is a frequency distribution of each. Figure 8 presents the spectral density of the cockpit vertical acceleration for a representative sea based aircraft at zero speed in head seas. The area under the curve is acceleration. The g's and peak frequencies (ωp) at which the highest g's are encountered are:

$H^{-1/3}$ (ft)	g's	ωp (RAD/SEC)	fp (HZ)
4	.085	1.65	.263
15	.11	1.1	.175
30	.12	0.7	.111

These significant wave heights are roughly equivalent to sea states 3, 6 and 7 respectively. Note that the peak frequencies at zero forward velocity in head seas are not always where the human is more sensitive to vertical acceleration (about 0.18HZ). At sea states below 6, the accelerations occur at frequencies higher than .18 Hz.

Figure 9 overlays the 25% motion sickness incidence (MSI) limits for unadapted, untrained subjects derived using sinusoidal accelerations with a center frequency of the one third octave bands as indicated (see Section 3.3) of Figure 5 with the representative sea based aircraft accelerations of Figure 8. This comparison indicates that motion sickness is not likely to occur at average sea states because the accelerations are low and the frequency is above the frequency of higheset incidence of sickness (.18 HZ). As the sea state increases, to sea state 5 and higher, motion sickness is possible after several hours of operation for untrained, unadapted subjects. Remember that the MSI data were obtained using pure sinusoidal accelerations in narrow frequency bands and not with the broad frequency bands more representative of actual sea state conditions.

MSI data using actual sea spectrum motion needs to be developed for a proper comparison. Based on discussions with Human Factors Research personnel, these limits would be higher (with less expectancy of motion sickness) than the MSI limits shown. Thus, for the representative sea based aircraft motions shown, a very low probability of MSI is expected. Considering trained crews, motion sickness should not be a problem at zero speed in head seas.

Comparing the motions of a representative sea based aircraft (about 0.1 g RMS), a DE-1040 has vertical accelerations of .09, .11 and .15 g's RMS at 10, 20 and 30 knots at sea state 5 at a mid point on the helo platform (see Reference 9). These g levels increase to .11, .14 and .22 at sea state 6, depending on the ship heading. Extreme bow and stern locations have higher motion levels with g levels exceeding .3 g's RMS.

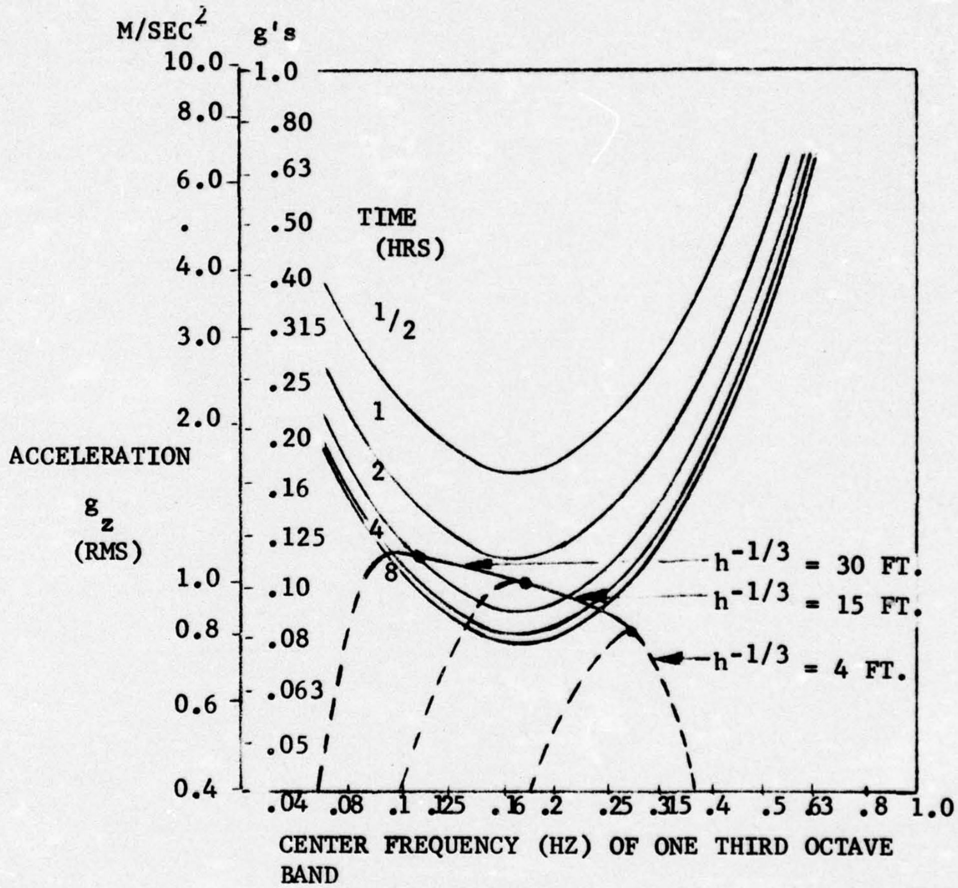

Figure 9. Comparison of Representative Sea Based Aircraft Motions with 25% Motion Sickness Limits for Untrained/Unadapted Subjects

Series 60 commercial ships show the following bow accelerations at 10 knots:

Significant Wave Height (ft)	Vertical Acceleration g's RMS
10	.24
20	.50

Based on the known motions of destroyers and other Navy vessels, a sea based aircraft operating in the surface following mode will have "relatively" mild motions. Roll stability will be vastly improved over a destroyer through the use of wing tip floats. Roll angles of 4 to 5 degrees RMS at 10 knots are typical at sea state 6 for a DE 1040. The lateral displacement for the DE 1040 at 10 knots and sea state 6 in quartering seas equals or exceeds the vertical displacement (4.5 to 5 feet RMS). The longitudinal displacement can also be significant for a destroyer.

3.5 Suggested Vehicle Low Frequency Motion Limits

Based on the information in the preceding sections, a set of sinusoidal and random low frequency motion limits are specified in Table 1. The very uncomfortable / unacceptable limits are where a significant mission performance disablement is considered to occur. The sinusoidal limits are based on known ship motions and Navy operations. Vertical sinusoidal accelerations of 0.10 g's RMS are typical and "comfortable" for trained/adapted crews. A 0.30 g's RMS level for sinusoidal accelerations are considered very uncomfortable and will result in unacceptable ASW mission operations. It should be remembered that .3 g RMS is below the level destroyers and commercial ships have during heavy seas. If the maximum g level is too low, it in effect places a restriction on the maximum sea state of operation of the craft. The lateral limits are based on the vertical limits and adjusted downward due to the belief that the human tolerance is lower laterally at low frequency (see Figure B-4).

The random motion limits are somewhat higher than the sinusoidal limits based on the data contained in Reference 10 which indicated representative random on water motions of .20 to .25 g's per 3 seconds being very uncomfortable and inducing motion sickness. The time base (3 or 6 seconds) is based on data from Reference 10. These limits can be compared to those of Reference 11, where a long term tolerable limit of 0.10 g and a severe-less than one hour limit of 0.5 g RMS are suggested.

Table 1 . Suggested Low Frequency Motion Limits for Sea Based Aircraft

	Low Frequency (.06-.60 Hz) Motion		
	Vertical g's	Lateral g's	Roll Rate
I <u>Sinusoidal Motion (2 Hours Time)</u>			
Comfortable/Acceptable Operations	.10 g's RMS	.05 g's RMS	4 Deg/Sec
Very Uncomfortable/Unacceptable Operations	.30 g's RMS	.15 g's RMS	10 Deg/Sec.
II <u>Random Motion (Spikes)</u>			
Comfortable/Acceptable Operations	.12 g's/3 Sec.	.08 g's/3 Sec.	N/A
Very Uncomfortable/Unacceptable Operations	.35-.40 g's/ 6 Sec.	.20 g's/6 Sec.	

The roll limits are based on Reference 12 which specifies an angular acceleration threshold of 1 to 2 degrees/sec^2 for 10 or more seconds (or 100 degrees in 10 seconds). The threshold is higher for short periods (see Figure 10).

Random roll rate limits are not considered applicable.

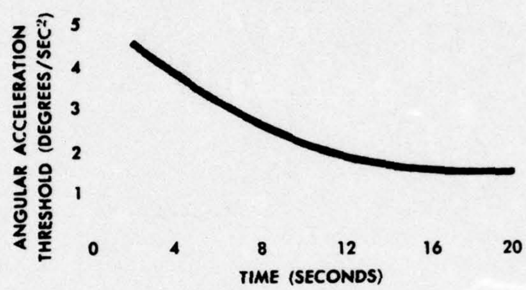

Figure 10. Angular Acceleration Limits

3.6 Heating, Ventilation, Air Conditioning and Visibility

Standards for heating, ventilation, air conditioning and visibility are given in References 4, 5, and 12. Reference 5 indicates the following heating and ventilation requirements for shipboard operation:

Heating - The crew compartment shall be provided with a heating system capable of maintaining temperatures above 68°F (20°C) during occupancy when personnel are not wearing Arctic clothing and exposure is for extended duration (i.e., more than 3 hours). When occupants are wearing Arctic clothing in cold environments, the crew compartment temperature should conform to cold environment requirements of HEL-STD-S-6-66.

Ventilation - Outside fresh air shall be supplied at minimum rate of 20 cu. ft. (0.43 cu. m)/min./person. Air flow rates for hot-climate operation (temperatures above 90°F (32°C) shall be maintained between 150 and 200 cu. ft. (4.25 and 5.66 cu.m)/min./person. The ability to vary ventilation and temperature to improve conditions for sea sickness avoidance is desirable. A cold blast of air at crew stations may be necessary to provide an alternate to "going topside". Air conditioning is considered a definite requirement for equatorial and hot weather operation.

Visibility - The heating-ventilating system shall be designed to minimize degradation of visibility due to frosting or misting of the windshield.

Reference 12 indicates the following desired comfort zone.

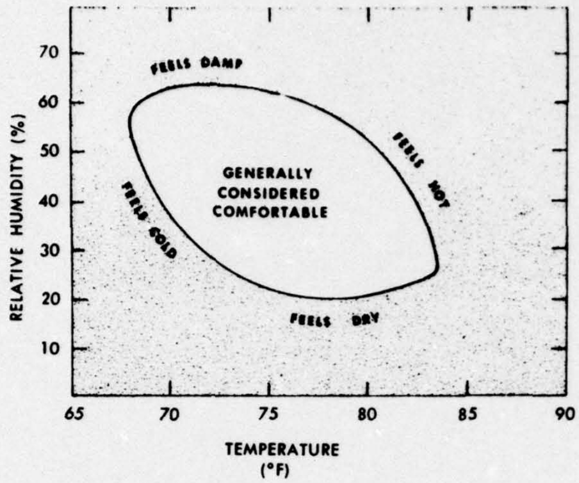

Figure 11. Desired Comfort Zone

Visibility requirements are as follows:

Night Operation - Indicators required by the vehicle operator during night operation shall be illuminated. The display luminance shall be adjustable from 0.02 to 1.0 ft-L (0.07-3.43 cd/m). Blackout lighting systems, if required, shall be designed to preclude accidental operation of external lights and signals.

Visual Field - The operator shall have forward visibility through a lateral visual field of at least 180^{o} (preferably 220^{o}).

General illumination levels are given in Reference 12 as follows:

TASK CONDITION	LEVEL (foot candles)	TYPE OF ILLUMINATION
Small detail, low contrast, prolonged periods, high speed, extreme accuracy	100	Supplementary type of lighting. Special fixture such as desk lamp.
Small detail, fair contrast, close work, speed not essential	50-100	Supplementary type of lighting.
Normal desk and office-type work	20-50	Local lighting. Ceiling fixture directly overhead.
Recreational tasks that are not prolonged	10-20	General lighting. Random room light, either natural or artificial.
Seeing not confined, contrast good, object fairly large	5-10	General lighting.
Visibility for moving about, handling large objects	2-5	General or supplementary lighting.

Figure 12. General Illumination Levels

3.7 Volume

Crew station design requirements are also discussed in Reference 5, Page 193. The following work space dimensions are presented:

	Light Clothing in. (cm)	Bulky Clothing in. (cm)
Minimum height allowance for standing	76 (193)	78 (198)
Minimum height allowance for crawling	31 (79)	34 (86)
Maximum depth of objects which must be reached into	23 (58)	21 (53)
Minimum width allowance for passing body	23 (58)	27 (69)
Minimum thickness allowance for passing body	13 (33)	16 (41)
Minimum height allowance for bending or kneeling	48 (122)	50 (127)

Reference 12 indicates the passenger densities vs. trip duration as shown in Figure 13.

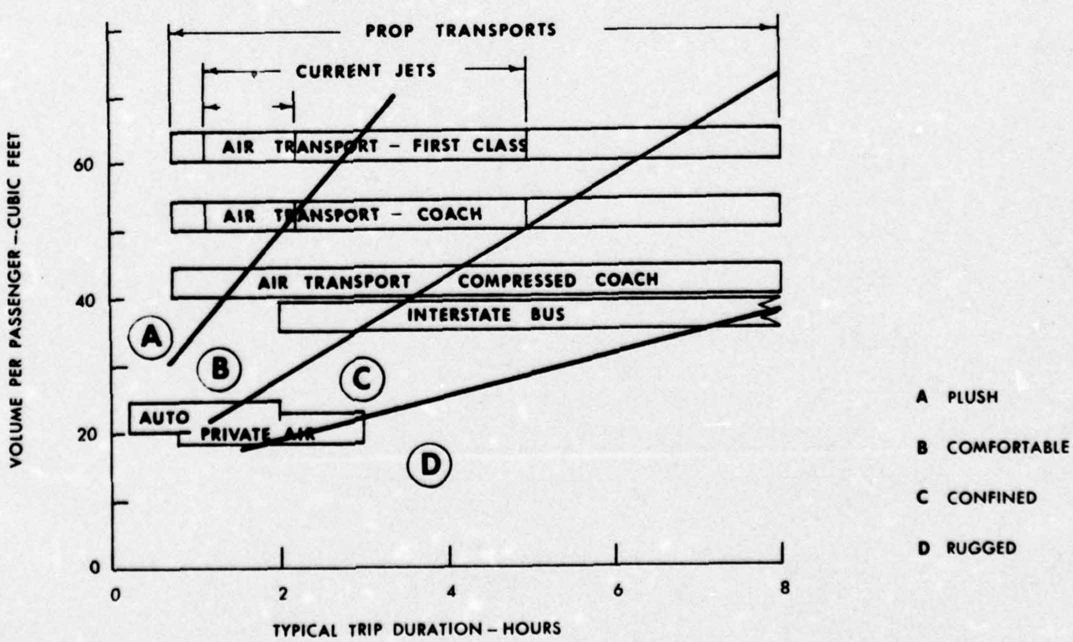

Figure 13. Passenger Densities Vs Trip Duration

One of the many factors which contribute to fatigue may be found in the space provided for passengers in transportation vehicles. In Figure 13 the volume per passenger vs duration of exposure has been estimated. Such estimates are based upon experience rather than on the basis of research evidence. One major aircraft manufacturer uses the following typical standards: nominal design compartment-volume per passenger, 50.5 cubic feet; compartment contents proportioned 77.5 per cent for seating, 3 per cent for door aisles, 6 per cent for coatracks, and 7.5 per cent for buffets; seat spacing between seat rows, 38 inches.

Work programming is an essential consideration in minimizing potential fatigue build-up. Although most persons are conditioned to a normal 8-hour workday, with the rest of the 24-hour cycle devoted to a combination of rest and recreation, it is perfectly feasible to create other work-rest cycles which maintain useful work levels.

3.8 Motion Sickness - Effects and Prevention

Equilibrium and orientation are maintained mainly through the use of three sensory modes: the visual sense, the vestibular sense and the proprioceptive (subcutoneous - kinesthetic) sense (Reference 14).* Motion sickness normally originates from stimulation of the vestibular organs. A loss of stability in the vestibular system is caused by repetitive sensory inputs that are abnormal in terms of the control vestibular patterning encountered (Reference 15).

Reference 14 states that about 50 percent of all people have been motion sick at one time or another. Some of the symptoms of motion sickness are apathy, headache, stomach awareness, pallor, perspiration, nausea, vomiting and prostration, usually in that sequence. Motion sickness includes air sickness, sea sickness, train sickness, car sickness, amusement-park-ride sickness, etc. The above motion sickness symptoms can be elicited by looking at motion pictures of heaving and pitching ocean vessels or while looking through a microscope and moving the slide back and forth under the objective in search of objects. For example:

During World War II ten percent of all flight students became air sick during their first ten flights. The rate ran to 50 percent for other aircrew members. Under very unfavorable conditions, as high as 70 percent of the airborne troops became airsick and were, to some degree, temporarily disabled on landing. The same was true of amphibious assault troops. Current estimates as to the number of Air Force pilot trainees that get motion sickness run about 18 percent. About 40 percent of all aircrews become motion sick during some phase of their training.

* See the Definitions Sections for word definitions.

What causes sea sickness?

Reference 16 states that "after an analysis of ship movements and calculation of the maximal acceleration values for a normal-sized passenger vessel on high seas, it is concluded that angular acceleration is unimportant in the elicitation of sea sickness. The vertical up-and-down motions of a ship are the most important, and experimental motion sickness can easily be provoked in human beings exposed to vertical movements in rapid elevators or hoisting cranes. Deaf-mutes with reactionless vestibular systems* have no symptoms of motion sickness after exposure to these rapid elevator movements.

Studies by Professor Ralph Stone indicate that stimulus of the head is extremely important in low frequency motion sickness. Good correlation was found with lateral motion (roll induced) in ride comfort tests using busses.

Results of hydromechanical studies and experiments on labyrinth models and temporal bones have shown that, when a person is exposed to linearly accelerated horizontal and vertical movements or to the movements of a ship on a heavy sea, pressure variations with accompanying displacements and flows in both the perilymph and the endolymph must occur at every point in the contents of the labyrinth. These pressure variations affect both labyrinths at the same time, but the momentary pressure in the corresponding points of the two labyrinths will seldom be exactly the same during these varying motions. It seems very probable that these pressure variations in the fluids of the labyrinth are of such a magnitude that the transmitted excitatory effect will create manifest symptoms of motion sickness.

It thus seems justifiable to assume that the symptom complex of motion sickness arises from the two receptor systems of the labyrinth: the otoliths and the ampullar cristae.

The intermittent headache and some of the psychic symptoms accompanying motion sickness may be largely due to the intracranial pressure variations caused by the linear acceleration movements.

Note that the domino effect (psychogenetic) of seeing another member of the crew vomiting or getting sea sick causes a high level of sea sickness. About 70% of frank emesis is induced through the psychogenetic effect.

Highly motivated crews have a significantly decreased susceptibility to motion sickness.

*See Section 5.0.

Reference 17 contains a review of about 16 studies on motion sickness. All references except two considered vibration in the vertical direction. The dominant frequency range was .15 to .3 Hz. High levels of sickness (50% or more) occurred at about .3 g's RMS. However, one study indicated the effect of pitch and roll where 62 percent of the subjects became sick with about .13 g RMS in 30 minutes. Other tests indicated that if the subject was placed in rotating seats, because of the additional induced coriolis effect, sickness levels were higher. Tests indicated that eyes open, head free had the lowest sickness levels. To avoid motion sickness, acceleration should not exceed .01 g's RMS.

These low g and frequency levels can be encountered in any displacement type vessel. Riding on the water in a life raft or wave contouring vessel at zero speed can cause RMS g levels of .1 g RMS. Obviously, any vessel that operates on the ocean surface in the displacement mode can cause motion sickness. Motion sickness prevention either through training, adaption, etc., is needed to reduce the incidence of sea sickness. Graybiel (Reference 18), had demonstrated by incrementally increasing coriolis accelerations to otherwise highly stressful levels, that motion sickness can be prevented in humans. Reference 14 indicates that "most people habituate to motion-sickness-producing stimuli to the point where they can effectively carry out assigned tasks. Those who have unusually stubborn or unmanageable motion sickness tendencies can be trained to have a markedly lesser degree of susceptibility if they are properly motivated." Tests indicate that the human body can adjust itself to sinusoidal vibration within a short time. Random vibration shows a higher restless activity level of muscular system reaction. It is apparently easiest to adjust to the lower frequencies of sinusoidal motions. This may explain the shape of the curves in Figure 7 which show that sea sickness incidence tends to level out with time. Repeated tests over time do show significantly lower levels of motion sickness with a high level of retention. (See Figure 14 from Reference 19). Remember that severe pure sinusoidal motion (0.33 g's RMS) yields a higher incidence of motion sickness but also hastens habituation. Based on the information of Reference 19, pure sinusoidal motion is considered to cause a higher incidence of motion sickness than does a representative sea state spectrum (irregular random waves). This was the experience of the author and other subjects who have experienced both sinusoidal and representative irregular wave motion.

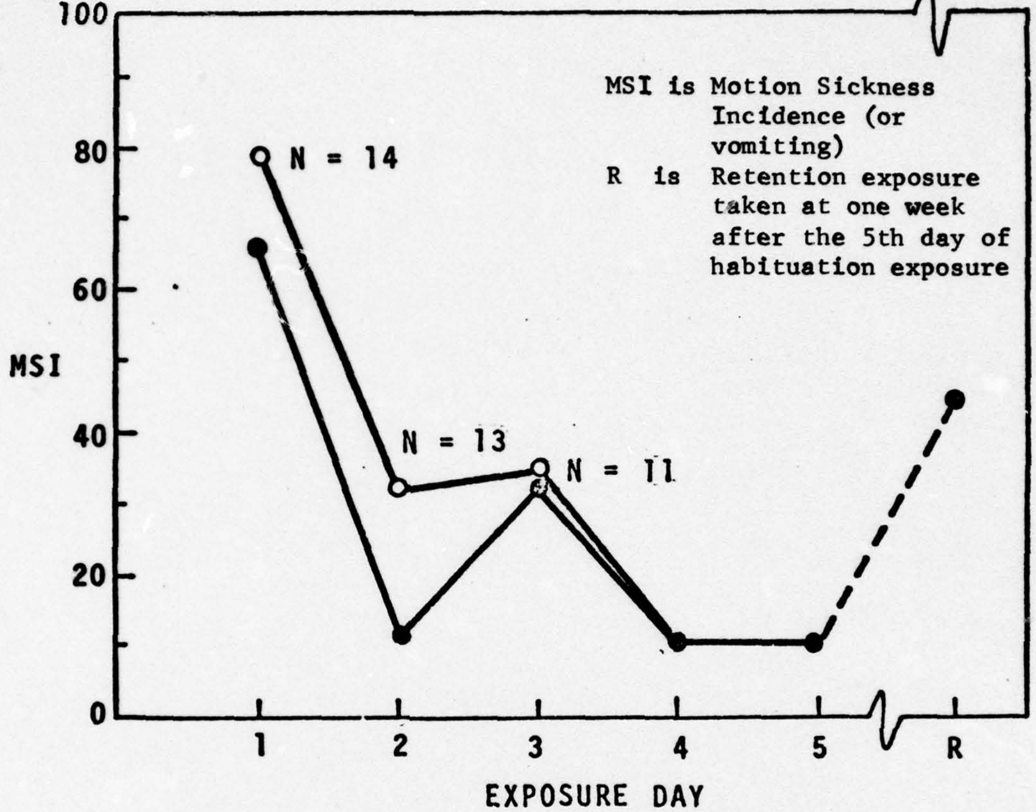

Figure 14. MSI over five daily 2-hour habituation exposures and retention of habituation after 1 week. Motion was vertical sinusoidal oscillation at 0.25 Hz and 0.33 RMS g (N = 9, closed circles.)

Reference 20 indicates that some drugs can significantly increase a person's resistance to motion sickness. Properly selected pharmaceuticals may aid in controlling motion sickness.

Standard Navy selection procedures using the Barony chair and/or caloric irrigation of the ears are very effective in eliminating approximately 1% of the population who do not seem to be able to adapt to the mobile environment. Other selected crew members will adapt rapidly (hours) to the anticipated environments without special adaptation or training procedures (discussions with James A. Green).

3.9 Sea Based Mission Considerations

Perhaps one of the most significant aspects of sea sickness are the side effects of performance degradation, fatigue, drowsiness (soporific or sopite syndrome) and loss of interest or depression in performing the assigned task. Reference 21, addresses drowsiness, one of the cardinal symptoms of motion sickness (termed the sopite syndrome). Drowsiness may occur before and after actual motion sickness (e.g. vomiting). Sleep has a strikingly recuperative effect on sea sickness in that it restores autonomic (the human vegetative nervous system) balance. The lethargy and drowsiness induced by on-water motion is not unpleasant and is referred to as a desirable relaxing experience. Nevertheless, there may be a measurable decrease in performance due to fatigue and/or drowsiness depending on the mission, assigned tasks and mission motivation or importance. Human performance tests need to be made for the sea based aircraft missions to establish the effect of different sea state conditions on crew performance and crew requirements.

Discussions with Mr. Alvah Vittner, Human Factors Engineering Branch, Naval Missile Center, Pt. Mugu, California, indicate the need to provide windows for a sea horizon reference as an aid to avoiding sea sickness. Mental concentration on mission related tasks is needed to take one's mind off thinking of getting sea sick. Providing berths for sleeping or resting is also desirable as an sickness avoidance aid. Normal Navy crews tend to need more sleep when at sea and particularly in rough seas. An operator on station for eight hours, if susceptible to motion sickness, may want to spend part of his free time in the bunk.

A mission analysis needs to be performed to establish crew needs, mission operating times and appropriate mission related motion criteria.

4.0 CONCLUSIONS AND RECOMMENDATIONS

The primary questions addressed in this report (see Section 1.1) are: (1) What are the human limits of motion, comfort and volume for a surface following aircraft? and (2) What questions need to be answered to quantify these limits? The suggested low frequency human limits of motion are presented in Table I, page 13, and are as follows; 0.30 g's RMS vertically and 0.15 g's RMS laterally for the frequency range of .06 to .6 Hz. Very uncomfortable or unacceptable operations for sea based aircraft on representative ASW type missions are considered to exist above these motion limits. These motion limits apply to sea spectrum (generally sinusoidal in nature) motion. Roll rate limits of 10 degrees per second are also considered applicable for unacceptable operation.

Sea based aircraft motions are less severe than those of present Navy destroyers and proposed advanced Naval vehicles such as surface effect ships (see Reference 13). Sea based aircraft head sea motions at zero speed are primarily of the very low frequency, .1 to .3 Hz and low RMS g's, about 0.1. A complete definition of the on water motions (quartering and following seas) of representative sea based aircraft needs to be obtained to establish the total motion limits of these craft. There is a need to define mission performance criteria for sea based aircraft to establish motion limits. Motion limits for trained-adapted crews performing an ASW tracking mission, for example, will be higher than for the transport of assault troops (a COD or VOD mission). Human operator training and adaption programs for crew training to staff these aircraft for these missions needs to be defined.

Human comfort zones are specified in Figure 11. Heating, ventilation, air conditioning and visibility limits are specified in Section 3.6 (as per MIL-STD-1472B, Reference 5). Provision of air conditioning and adequate ventilation is considered a definite requirement for hot weather operation.

Volume requirements are a function of mission duration and are difficult to specify (see Figure 13). Generally 20 cubic feet is considered a minimum. Long duration missions (over 6 to 12 hours) dictate bunks, toilet and eating facilities. Mission conditions and crew training are the important variables here.

A human factors study of operator needs for specified sea based aircraft missions needs to be performed to properly set limits for human comfort.

The overall conclusion of this report is that sea based aircraft missions are considered operationally practical from a human operator performance standpoint.

5.0 DEFINITIONS

Vestibular Process - The non-acoustic labyrinth portion of the inner ear containing otolith organs and semicircular canals that sense linear and angular accelerations and convert this energy into neural impulses and mainly through influencing motor behavior, aid in orientation of the upright and in eye-head-body coordination.

Proprioceptive (subcutaneous-kinesthetic) Process - The sensory process including pacinian corpuscles, neuromuscular spindles, golgi tendon organs and joint receptors. The pacinian corpuscles are tiny laminated ovoids buried deep in many body structures that respond to pressure and transduce this pressure into neural impulses. The last three provide kinesthetic or "muscle sense of position" as they respond to muscle or tendon stretch.

Etiology - study of the causes of diseases.

Nystagmus - an involuntary oscillation of the eyeball, usually lateral but sometimes rotatory or vertical.

Epiphenomenon - a secondary or additional symptom or complication arising during the course of a malady.

Motion Sickness - The common signs and symptoms of motion sickness are pallor, cold sweating, nausea, and vomiting. Based on Reference 7, and other indicated references therein, vomiting is used as the cardinal indication of motion sickness since task performance ceases and more subtle evidences of performance decrement prior to vomiting (sickness) have not been consistently found.

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PERSONNEL CONTACTS DURING STUDY

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Mr. John H. Wykes/ Mr. Chris Borland	B-1 Division, Rockwell International, El Segundo, Calif.	B-1 Ride Criteria Index	Casnet 8-259-3506 213-670-9151
Mr. Mike McCauley/ Dr. James F. O'Hanlon	Human Factors Research, Inc., Goleta, Calif. 93017	Human Motion Sickness Limits	805-964-9117(H) 805-968-1071(O)
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APPENDIX A

BIODYNAMIC EFFECTS

APPENDIX A

BIODYNAMIC EFFECTS

This appendix has been taken from Reference 3. It is included here because of its relevance to human vibration limits.

Biodynamic effects are those phenomena which consist of body movement reactions to vibration inputs. When the human body is vibrated, it does not react in a rigid and passive manner; rather, the body and its organs can be likened to a complex set of masses, springs, and dampers.

From a design standpoint, probably the most useful biodynamic data are those dealing with whole body transmissibility - - that is, the ratio of output to input motion. Resonances of internal organs, though of value, are not vital to system design because dangerous organ resonances are thought to occur only at severe intensities where subjective tolerance limits (often associated with pain) are reached.

Two terms which are commonly used with reference to biodynamic response to vibration are mechanical impedance and transmissibility. Mechanical impedance is defined as the ratio of applied force to the resulting body or organ output velocity. Transmissibility is the ratio of body output motion to applied motion in terms of velocity, amplitude, or intensity.

Sinusoidal ±gz Vibration

Seated and Standing Subjects - Dieckmann (1958) measured transmissibility and mechanical impedance in comparing the biodynamic effects of sitting and standing postures. He found 4 to 5 Hz to be the resonant frequency at the head and shoulders of the seated subject. When the subject is standing, impedance is greater at 5 Hz with a secondary peak at about 12 Hz.

Shoulder transmissibility in standing subjects during 1 to 27 Hz was recorded by Chaney (1965). He reported a maximum transmissibility ratio of 1.5 for the 4 to 6 Hz range, with attenuation below 2 Hz and above 7 Hz (Figure A-1). Note that the transmissibility at very low frequency should approach unity. Measurement procedure errors may account for this.

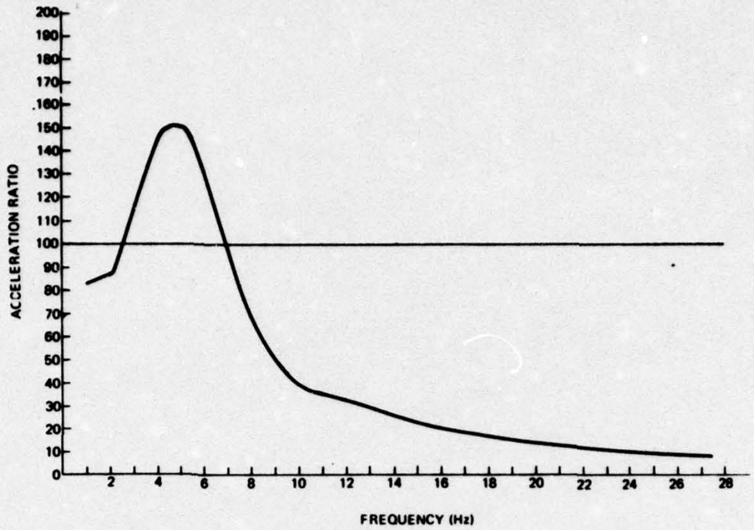

Figure A-1. Shoulder acceleration (transmissibility) expressed as a percentage of table acceleration for standing subjects. (From Chaney, 1965)

Random g_z Vibration

In 1966, Hornick and Lefritz recorded acceleration at pilots' heads during simulated LAHS flight with various RMSg_z levels from zero to 12 Hz (Figure A-2). For a 10 minute sample, output acceleration is greatest from 4 to 6 Hz, with attenuation below 2.5 Hz and above 11 Hz. These results agree very well with those obtained during sinusoidal conditions.

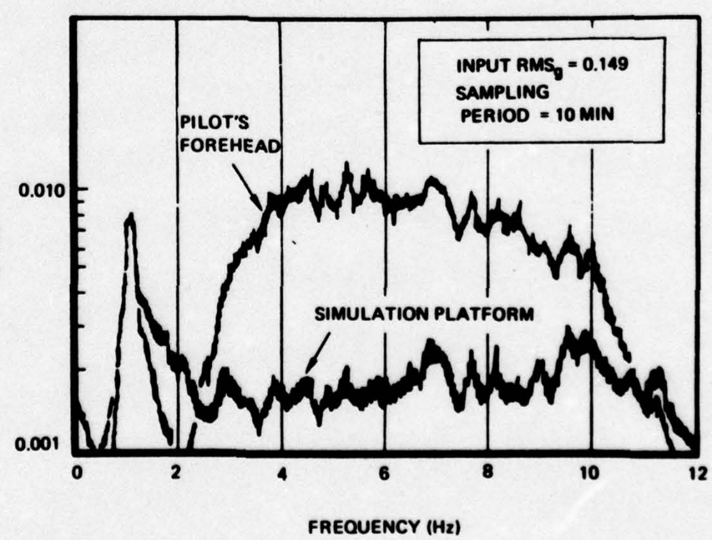

Figure A-2. Biodynamic transmissibility during random g_z vibration. (From Hornick & Lefritz, 1966.)

Other Axes and Postures

The head motions of seated and standing subjects in $+1G_z \pm ng_x$ conditions were recorded by Dieckmann (1958). Figure A-3 shows that the head follows the horizontal motion in a flat ellipse at low frequencies. As 5 Hz is reached, the elliptical shape of the head movement becomes vertically oriented for the standing person and becomes circular for the sitting person.

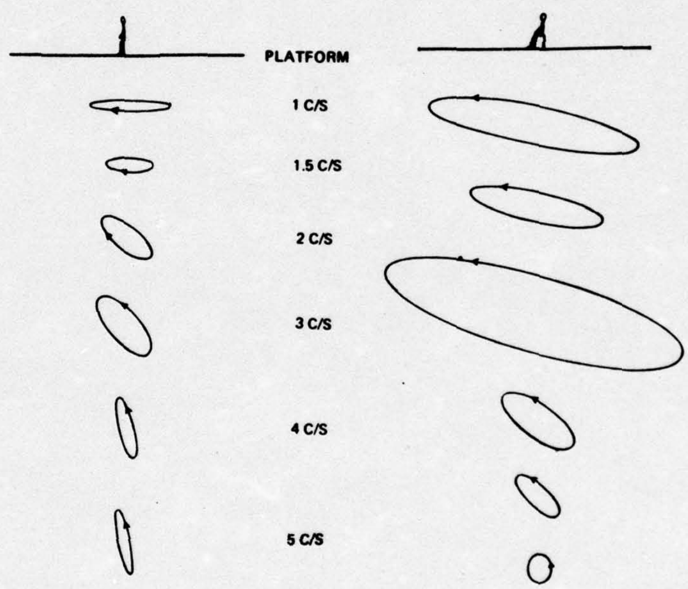

Figure A-3. Head movement of standing subject (left) and sitting subject (right) with $\pm g_x$ vibration. (From Dieckmann, 1958.)

Hornick, Boettcher, and Simons (1961) also recorded transmissibility at the head, during $+1G_z \pm ng_y$ conditions. Figure A-4 reveals that from 1.5 to 5.5 Hz, the body does an excellent job of attenuating motion as recorded at the head during the side-to-side vibration. The least attenuation at 1.5 Hz suggests that $\pm g_y$ resonance lies somewhere near that frequency.

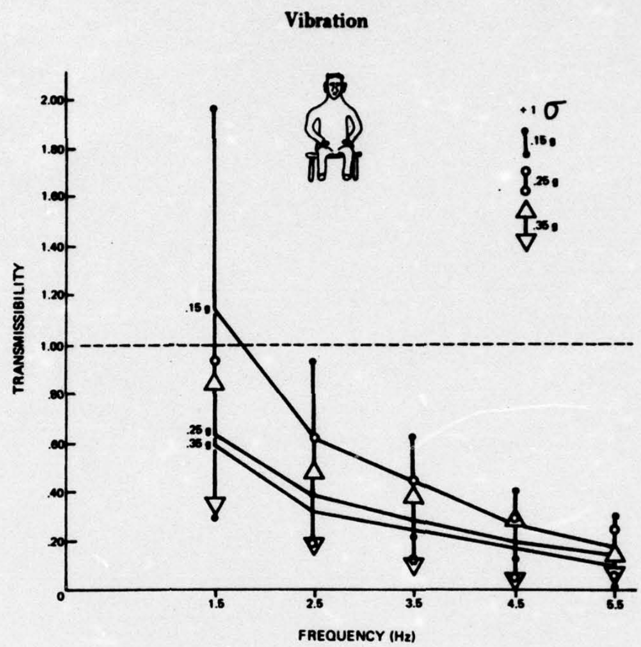

Figure A-4. Transmissibility at the head during $\pm g_y$ vibration. Standard deviations appear for each mean for 20 subjects. (From Hornick et al., 1961.)

Summary of Biodynamic Effects

Test results indicate:

1. Internal organs have unique resonant frequencies which can differ in each axis.

2. Whole body resonance for seated subjects is in the region of 4 to 6 Hz in the $\pm g_z$ axis.

3. For the seated subject, maximum hip amplification occurs at higher frequencies, about 10 Hz, in the $\pm g_z$ axis.

4. Motion experienced in the seated subject at the upper torso may be amplified from 1.5 to 4.0 times at the resonant frequency.

5. Use of helmets modifies head motion, and it is suggested that the helmet-free condition is better than the helmet-restrained condition.

6. Standing subjects, with motion in the $\pm g_z$ axis, have a major body resonance near 4 to 6 Hz. A secondary resonance occurs near 12 Hz. Standing with the legs bent serves to attenuate the input vibration, but fatigue occurs and effectiveness of this as a damping technique is gradually lowered.

7. When seated and experiencing $\pm g_x$ vibration, the lower body amplifies the motion, but motion is attenuated at the head. Resonance is above 5.5. Hz.

8. When seated and experiencing $\pm g_y$ vibration, motion in the upper torso is attenuated, but maximum response occurs near 1.5 Hz.

APPENDIX B

SUBJECTIVE VIBRATION (MOTION) TOLERANCE LEVELS

APPENDIX B

SUBJECTIVE VIBRATION (MOTION) TOLERANCE LEVELS

This appendix has been taken from Reference 3. It is included here because of its relevance to on water motion human limits.

Sinusoidal $\pm g_z$ Vibration

The system designer is confronted with a large body of conflicting data when he attempts to determine vibration levels which are subjectively acceptable to man. It is true that levels which are virtually imperceptible to man can be identified, as well as those where extreme pain or discomfort occur. However, the designer is most often faced with the nebulous area between the extremes. Tolerance limits are treated here along with subjective levels since a tolerance limit may be considered as the uppermost subjective level. A true tolerance limit would be based on pathological data such as organic damage or actual mortality. Man is not used as an experimental animal for such purposes; therefore, estimates of tolerance limits are based on subjective reactions to pain and anxiety or fear.

The basic problems in defining valid subjective levels are: (1) interpersonal variability - - different persons label the same intensity level with different terms; (2) intra-personal variability - - the same individual describes an intensity level as "disturbing" at one time, and "hardly noticeable" at another; (3) situation specificity - - a particular intensity level is perceived differently depending on whether the individual is in an aircraft, an automobile, or in his home; and (4) semantics - - a lack of consistent definitions of terms such as "annoying," "objectionable," "disturbing," etc.

Subjective levels and tolerance limits presented in this section, therefore, should be used with some degree of caution. The system designer should not believe, for instance, that a potential change of 0.10g suddenly places his system in an "objectionable" range. He must use the described levels advisedly, knowing that while they may be the best data available, limits are quite flexible because of the factors mentioned above.

Historically, subjective studies have largely provided the basis for proposed vibration standards. Various schemes have been used in attempts to provide standards which could be universally applied to the population. Typically, a set of frequency-intensity curves are provided representing different levels of subjective reaction; then conversion functions might be added to arrive at levels for different axes, for random motion, and for duration of exposure.

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Two agencies have been active in trying to define acceptable standards. In the United States, Working Group S3-W-39 of the American National Standards Institute (ANSI) is writing standards with respect to annoyance, work interference, and hazard. Technical Committee ISO/TC 108/WG 7 of the International Organization of Standardization (ISO) is determining thresholds of vibration and shock acceptable to man (ISO, 1970; Hornick, 1969) (Now ISO 2631, 1974, see Reference 4).

Figure B-1 illustrates wide variability in subjective tolerance levels reported by subjects exposed to 1 to 27 Hz to sinusoidal g_z vibration in studies by Parks and Snyder (1961) and Chaney (1964) using identical facilities.

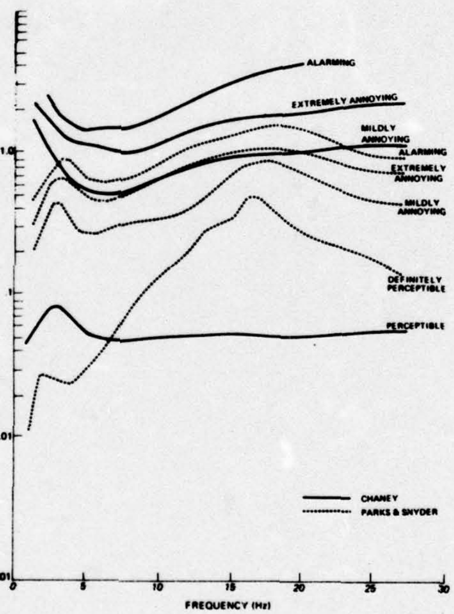

Figure B-1. Subjective tolerance curves comparison. (Chaney, 1964).

"Notice that depending on the frequency, there can be as much an order of magnitude difference in subjective tolerance levels. The very low frequency region (around 1 Hz) has a high variability both in degree and slope of the trend curve."*

* Author's comment.

A psychophysical approach to the quantification of subjective levels has recently been devised by Shoenberger and Harris (1969), whereby magnitude estimation and intensity matching replace qualitative descriptions. For each frequency, results are plotted as straight line functions on log-log graphs of subjective intensity versus physical intensity. Subjects then match the intensity of 9 Hz at 0.08, 0.16, 0.26, 0.36, 0.46, and 0.56 g_z with vibration at each of the other six frequencies. According to Shoenberger and Harris, equal intensity curves from the magnitude estimation data show the same general shape and comparable levels as corresponding curves determined experimentally using the intensity matching procedures. The derived curves from the intensity matching and magnitude estimation data are based upon a value of 0.006 g_z for the threshold of vibration perception at 9 Hz, with the six acceleration levels then corresponding to the multiples of that base. These results indicate that subjective response to vibration can be assessed by techniques similar to those used in acoustics, and that they could eventually be used for estimating the severity of complex vibration conditions.

Random g_z Vibration

Table B-1 summarizes reactions to random g_z vibration.

Other Axes

Lee and Pradko data (1968) support the notion that the g_x and g_y axes may not differ much for subjective comfort, and that these axes differ from the g_z axis as follows: below 4 Hz, comfort is lower for the g_x and g_y axes;*above 4 Hz, comfort is greater in the $g_x$and g_y axes.

"Annoying" and objectionable" levels for aircraft passenger situations were studied by Brumaghim (1969). Subjects were seated in aircraft seats in a simulator and experienced several types of vibration - - $\pm g_z$, $\pm g_y$, single and combined frequencies, single and combined axes, and combined frequencies and axes. These results also indicate that lateral $\pm g_y$ vibrations are more objectionable than g_z motion in the range to 3 Hz* (Figure B-2). Combined frequency tests were conducted in g_z and g_y axes to determine if reactions to multifrequency vibration could be linearly predicted from the values obtained for each frequency separately. That is, for the 1 and 4 Hz combination, halves of each separate frequency intensity called objectionable were summed as the predicted value for the combined frequencies. Brumaghim found good agreement between predicted and actual values. However, the results for prediction of combined axis vibration reactions were not good, again indicating the nonequivalence of the axes of motion with respect to subjective reaction.*

* Author's underlines

Table B-1

Subjective Reactions to Random g_z Vibrations

RMSg	Effect	Conditions	Source
0.80	Intense discomfort in abdomen and thorax; pain	5 Min. duration, 2 - 30 Hz	Dean, Farrell, & Hitt, 1967
0.70			
0.60			
	Refusal to exceed by varying aircraft flight parameters	Flying aircraft through turbulence.	Notess, 1963
0.50			
	Refusal to exceed by reducing the velocity of driven tanks	Driving tanks over rough terrain	Fernstron, Gschwind, & Horley, 1965
0.40	Occasional complaints of discomfort, fatigue, muscle tightness	3 hour duration	Schohan, Rawson, & Soliday, 1965
	Visual blurring, nose itch, face flutter, teeth chatter	40 min. duration, 1 - 1000 Hz	Dean, McGlothien, & Monroe, 1964
0.30			
	Some unpleasant effects	3 min. duration, 2 - 7 Hz	Woods, 1967
0.20	No subjective complaints	4 hour duration, 1 - 12 Hz	Hornick & Lefritz, 1966
	No subjective compaints	6 hour duration, 1 - 6 Hz	Holland, 1967
0.10			

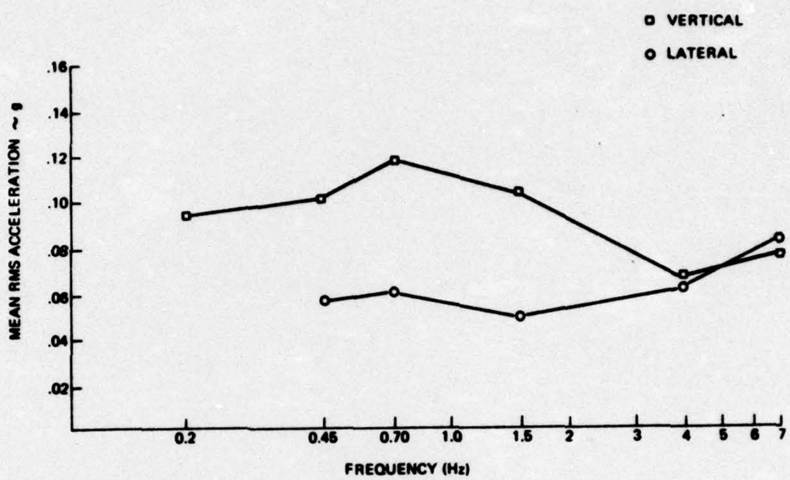

Figure B-2. Subjective "objectionable" response levels for $\pm g_z$ axes. (From Brumaghim, 1969.)

Temple and coworkers (1964) conducted a study with subjects semisupine at $+1G_x$ experiencing $\pm g_x$, $\pm g_y$, and $\pm g_z$ vibration from 3 to 20 Hz to evaluate tolerance endpoints for several couch support and head restraint configurations. The data indicate that tolerance is extremely sensitive to the type of support, and that complex interactions exist between type of support system and axis of motion.

Summary of Subjective Responses

Subjective levels and tolerance limits in older literature are not useful for design because they (1) are based on antiquated studies; (2) use grossly subjective semantics; (3) depend on "data" from one or very few subjects or "observers;" (4) do not account for variability; (5) do not account for duration; (6) do not account for personal variables; and (7) do not differentiate among axes. Certain agencies are in the process of defining limits which may become universally acceptable as design guidelines. However, these are not yet satisfactorily defined.

Two reviews have as their objective the exploration of the limit problem rather than the definition of discrete levels. Bryce (1966) explored the basis of the disagreements in the subjective comfort area and suggests that the most prominent discrepancies are attributable to the amount of restraint afforded by the body support. Gartley and Beldam (1967) explored the feasibility of establishing acceptable exposure criteria and conclude that "the inconsistencies and general lack of agreement ... make it impossible to develop realistic vibration exposure criteria ..."

Beyond the subjective data reported in Table 7-6*, it can reasonably be stated that subjective comfort to g_y and g_x motion is less than for g_z below 4 Hz; above 4 Hz, g_z is likely to be more disturbing than for the other axes. Published exposure limits at this time are difficult to justify and must be applied cautiously.

APPENDIX C

DEVELOPMENT OF A MILITARY SPECIFICATION

FOR

ON-WATER MOTION OF SEA BASED AIRCRAFT

APPENDIX C

DEVELOPMENT OF A MILITARY SPECIFICATION FOR ON-WATER MOTION OF SEA BASED AIRCRAFT

Introduction

There is presently no military specification applicable to on-water motion of sea based aircraft. The frequency range of .15 to .3 Hz is below the frequency range of the ISO 2631 (Reference 6) or MIL-STD-1472B (Reference 5) which covers frequencies of 1 Hz and above. Military Specification MIL-F-9490D for Flight Control Systems (Reference 22), does cover the frequency range of .1 to 1 Hz and defines a ride discomfort index which, with modification, could usefully be applied to the on-water motion limitations of sea based aircraft. This appendix addresses the modification of MIL-F-9490D for Sea Based Aircraft.

Military Specification, MIL-F-9490D, for Flight Control Systems

MIL-F-9490D (Reference 22) is a new general military specification for design, installation and test of military piloted aircraft flight control systems. It establishes inflight control and maneuvering limits for manual and automatic flight control systems (MFCS and AFCS).

Regarding manual systems, it includes longitudinal, lateral-directional, lift, drag and variable geometry control systems; their associated augmentation, performance limiting and control devices. Regarding automatic systems, it includes automatic pilots, stick or wheel steering, autothrottles, structural mode control (e.g. B-1 structural mode control) and similar control mechanisms. As a part of this specification, ride smoothing limits for AFCS and other FCS are defined in terms of short term and long term vertical or lateral axis vibration during in-flight turbulence. These ride smoothing limits are defined in terms of Ride Discomfort Index Limits which shall not be exceeded at any new station during flight in the turbulence level specified in Table B-1.

Table B-1. Ride Discomfort Index Limits

Ride Discomfort Index, D_i		Flight Phase Duration (Exposure Time)	Probability of Exceeding RMS Turbulence Intensity
Long Term Requirement	0.10	Over 3 Hours	0.20
	0.13	From 1.5 to 3 Hours	0.20
	0.20	From 0.5 to 1.5 Hours	0.20
Short Term Requirement	0.28	Less than 0.5 Hour	0.01

The requirements apply separately to each of the vertical and lateral axes due to the lack of agreement on method and limited test data available on combined axis accelerations (see Reference 23). Note that vertical ride discomfort is to be evaluated due to vertical axis turbulence only and lateral ride evaluated due to lateral turbulence only. No requirement is specified for roll gusts or longitudinal (pitch) gusts (Reference 23). Ride discomfort must not exceed the 0.10 or other pertinent long term limits in light turbulence. System saturation must not be so severe in turbulence at the 0.01 exceedance level that the 0.28 ride discomfort limit is exceeded. These requirements normally apply where a ride smoothing AFCS is specified or where ride smoothing is not specified and other AFCS modes may degrade ride quality.

The ride discomfort index, D_i is defined as:

$$D_i = \left[\int_{0.1}^{f_t} \left| W(f) \right|^2 \left| T_{cs}(f) \right|^2 \phi_u(f) df \right]^{1/2}$$

D_i = Ride Discomfort Index, (vertical or lateral)

$W(f)$ = Acceleration weighting function (vertical or lateral) 1/g (see Figure B-1)

$T_{cs}(f)$ = Transmissibility, at crew station, g/ft/sec

$\phi_u(f)$ = Von Karman gust power spectral density of intensity specified in Table B-1 and form specified in MIL-G-8785 (see Table B-2)

f = Frequency, Hz

f_t = Truncation frequency (frequency beyond which aeroelastic responses are no longer significant in turbulence)

where:

T = the longest time spent in essential flight phase segment in any mission/total flight time per mission.

Table B-2 specified RMS vertical gust amplitude versus altitude for selected exceedance probabilities. The relationship among vertical, lateral and longitudinal RMS intensities and scales as specified in MIL-F-8785 shall be used to establish intensities for lateral and longitudinal gusts. The listed turbulence intensity levels apply at the turbulence penetration airspeed V_G. At the maximum level flight airspeed, V_H these intensity levels are reduced to 38 percent of the specified levels. The mathematical forms of continuous random turbulence to be used in conjunction with the specified intensity levels are as specified in MIL-F-8785 and the airspeeds cited are as specified in MIL-A-8860.

Table B-2. RMS Gust Intensities $\phi_u(f)$ for Selected Cumulative Exceedance Probabilities, Ft/Sec TAS

FLIGHT SEGMENT	ALTITUDE (FT – AGL)	PROBABILITY OF EXCEEDANCE						
		2×10^{-1}	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}
TERRAIN FOLLOWING	UP TO 1000 (LATERAL)	4.0	5.1	8.0	10.2	12.1	14.0	23.1
	UP TO 1000 (VERTICAL)	3.5	4.4	7.0	8.9	10.5	12.1	17.5
NORMAL FLIGHT CLIMB CRUISE AND DESCENT	500	3.2	4.2	6.6	8.6	11.8	15.6	18.7
	1,750	2.2	3.6	6.9	9.6	13.0	17.6	21.5
	3,750	1.5	3.3	7.4	10.6	16.0	23.0	28.4
	7,500	0	1.6	6.7	10.1	15.1	23.6	30.2
	15,000	0	0	4.6	8.0	11.6	22.1	30.7
	25,000	0	0	2.7	6.6	9.7	20.0	31.0
	35,000	0	0	0.4	5.0	8.1	16.0	25.2
	45,000	0	0	0	4.2	8.2	15.1	23.1
	55,000	0	0	0	2.7	7.9	12.1	17.5
	65,000	0	0	0	0	4.9	7.9	10.7
	75,000	0	0	0	0	3.2	6.2	8.4
	OVER 80,000	0	0	0	0	2.1	5.1	7.2

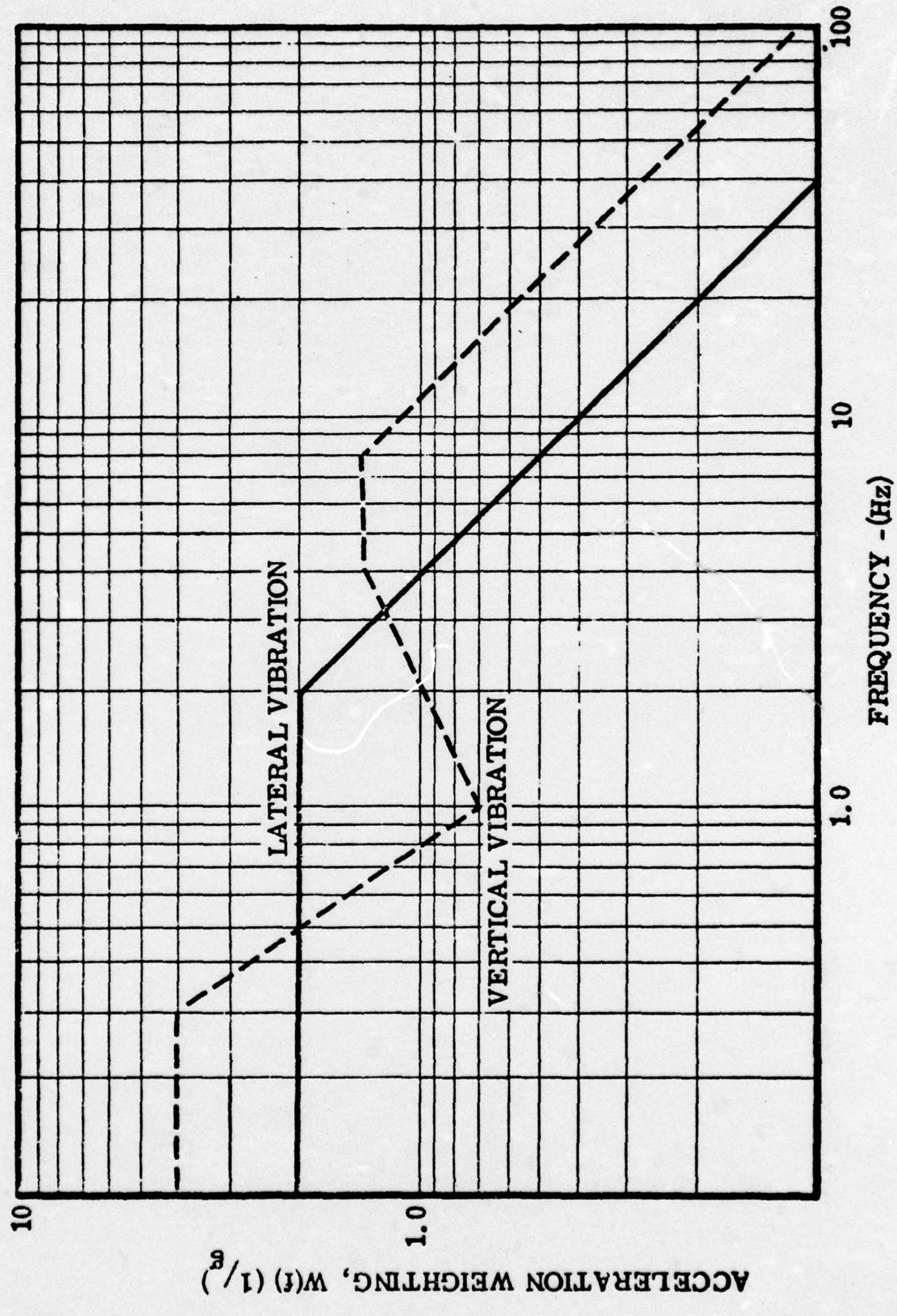

Figure B-1. Acceleration Weighting Functions

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The levels of ride discomfort specified are based on short term tolerance and long term tolerance. Data from References 6, 24 and 25, indicate that below a Ride Discomfort Index of 0.07, little or no degradation in crew performance or passenger comfort is expected. Above a Ride Discomfort Index of 0.28 the USAF references indicate crew action must be initiated to reduce the acceleration environment by changing flight path, altitude and/or airspeed. Figure B-2 illustrates unpublished data from a commercial airplane moving base simulator study in terms of incremental pilot ratings (Cooper scale) due to accelerations which also indicate a limit near 0.28 for an incremental pilot rating of 3. (Note that a satisfactory rating of 3.5 in calm air plus an incremental rating of 3 in turbulence yields a total rating of 6.5.)

The only known production ride smoothing system designed to date, the B-1 system used a vertical long term index near 0.10. The lateral B-1 requirement was more stringent. Commercial feasibility studies have used much more conservative design goals. Reference 26, for example, used an unweighted index of 0.03 in 0.01 turbulence. This is equivalent to an unweighted index of 0.015 in 0.20 turbulence at low level and is roughly a factor of 10 more stringent than the MIL-F-9490D criterion. The procuring activity, of course, may redefine the required values of the ride discomfort index to be used for specific procurements, based on unique mission requirements.

The B-52 is known for its marginal ride during low level penetrations. When compared to this long term criteria (3 hrs. = 0.10) the B-52 exceeds the criterion for medium and light gross weights and satisfies the criterion for heavier gross weights. Thus, for the initial penetration flight phase the B-52 ride is acceptable.

For later phases the ride is unacceptable, if the remaining low level flight phase exceeds three hours.

The Figure B-1 acceleration weighting functions are based on the MIL-STD-1472 human sensitivity curves, Reference 6, as extrapolated to lower frequencies by Reference 27. The extrapolations below 1.0 Hertz, especially for lateral vibration, are supported by a minimum of data. However, the values defined represent the best current consensus of experts within the 6750th Aerospace Medical Research Laboratory and reflect the current U.S. recommendation to the International Organization for Standardization for human exposure to vibration from 0.1 to 1.0 Hertz. The weighting functions defined are truncated at 0.1 Hertz and at high frequencies.

NOTES: 1. UNPUBLISHED BOEING DATA FOR COMMERCIAL AIRPLANES
2. DATA OBTAINED FROM MOVING BASE SIMULATOR STUDY

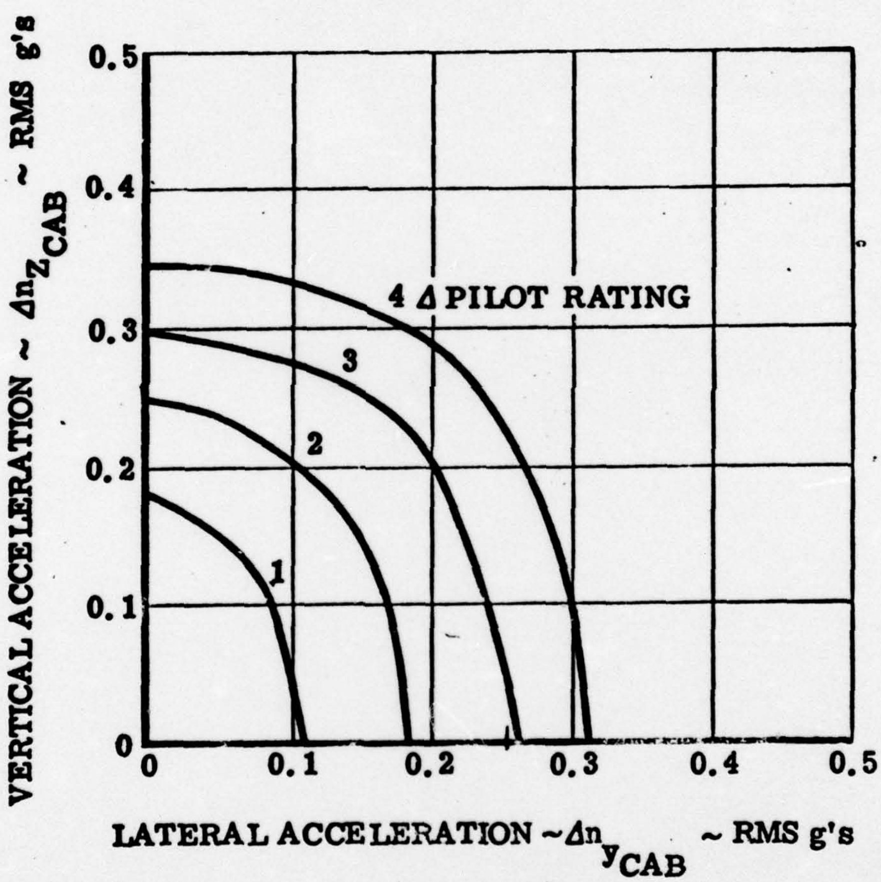

Figure B-2. Effect of Combined Acceleration On Pilot Rating

The reason for weighting function truncation is the limitations of the test equipment used to generate data upon which these curves are based. Moving base simulators can be used to simulate aircraft at low frequencies; however, the data obtained below 0.1 to 0.2 Hertz is of questionable value since continuous oscillations at these frequencies do not normally occur in flight. In many cases, the pilot or AFCS will control low frequency motions, effectively smoothing these oscillations and reducing the truncation error resulting from this approach (see Reference 28).

The intent of this requirement is to specify the ride experienced by the crew. Soft seats or other isolation techniques used should be considered in meeting this requirement. Care must be taken that relative motion between the crew member and his controls and instruments, resulting from isolation techniques, does not degrade crew performance. Visual problems, for example, can be aggravated by relative motion.

There are several current sources of literature available on ride smoothing systems. References 29 and 30 describe development of the B-1 ride smoothing system which was synthesized using the ILAF concept.

Note that the specification considers the same value of ride discomfort index, D_i, to apply to both vertical or lateral motion. Figure B-4 would indicate that the human is more sensitive laterally than vertically. The Ride Quality Specification for the B-1 aircraft considers different values of $\overline{H}_e$ (RMS of pilot tracking error response per unit RMS gust velocity). The values of $\overline{H}_e$ for vertical and lateral response are:

$$\overline{H}_{e_v} = .028$$

$$\overline{H}_{e_l} = .007$$

Since $D_i = \overline{H}_{\delta_u}$ and from Table B-2 δ_u = 3.5 FPS vertically and 4 FPS laterally;

$$D_{i_v} = .028 \times 3.5 = .098 \approx .10$$

$$D_{i_l} = .007 \times 4 = .028$$

Thus, the B-1 ride discomfort index is about four times more restrictive laterally than vertically.

MIL-F-9490D, which considers the same D_i index vertically as laterally differs from the B-1 ride quality specification in this respect. This difference should be resolved before application of MIL-F-9490D to sea based aircraft motion limits.

The acceleration weighting function (Figure B-1) indicates that lateral sensitivity is higher than vertical sensitivity in the frequency range of 0.5 to 3 Hz. This is in agreement with MIL-STD-1472A and ISO 2631 (References 5 and 6). This trend is considered correct based on available data.

The acceleration weighting function (Figure B-1) also indicates more sensitivity vertically than laterally at frequencies below .5 Hz. Based on the data of Figure B-4 and the fact that the B-1 ride discomfort index, which indicates lateral sensitivity is four times greater than vertical sensitivity (see Reference 24), this conclusion is suspect. These differences need to be resolved before application of MIL-F-9490D to sea based aircraft motion limits.

Application of the Ride Discomfort Index, Di, to On-Water Motion Limits of a Sea Based Aircraft.

Thus, the application of the Ride Discomfort Index, D_i, to on-water motion involves (1) modifying the gust power spectral density $\phi_u(f)$ to reflect the water wave power spectral density and (2) establishing a human transmissibility for the operator $T_{cs}(f)$ at his shoulder or head and modification of the acceleration weighting function W(f). $\phi_u(f)$ would normally be considered for a given sea state. For example, consider the following wave power spectral density $\phi_u(f)$ and operator transmissibility $T_{cs}(f)^2$:

Sea State	$\phi_u(f)$ (Feet/Sec)	Wave RMS g's	$T_{cs}(f)^2$ * $g^2/ft/sec^2/Hz$
3	3.5	.05	.000408
5	5	.1	.0008
7	8	.15	.0007

Then, for the frequency range of .1 to .3 Hz (or a .2Hz frequency band, from Figure B-1, W(f) = 4 (1/g) for vertical vibration and W(f) = 2 (1/g) for lateral vibration. From Figure A-2, note that the biodynamic transmissibility at the pilot's head during random gz vibration is extremely low and is estimated to be $\approx$ 0.001 at 0.1 to 0.3 Hz. This is for an input RMS g's of 0.149. Thus, the assumed transmissibility values of .000408 to .0008 would seem to be of the proper magnitude. Note that the transmissibility data of Figure A-2 is for a unit vertical velocity (one feet/second) for these conditions.

Considering vertical vibration in the .1 to .3 Hz frequency band then,

W(f) = 4 (1/g) and

$$D_i = \left[\int_{0.1}^{0.3} \left|W(f)\right|^2 \left|T_{cs}(f)\right|^2 \phi_u(f)df\right]^{1/2}$$

where for long term, D_i = 0.10 (over 3 hours) and for short term, D_i = 0.28 (less than 0.5 hours).

*Human transmissibility of input is unity, i.e., all wave acceleration is received and absorbed by the human.

Considering W(f), $T_{cs}(f)$ and Ø a (f) as constants independent of frequency:

$$D_i = \left[|W(f)|^2 |T_{cs}(f)|^2 \right]^{1/2} \left[\int_{0.1}^{0.3} \phi_u(f)\, df \right]^{1/2}$$

and $$D_i = \left[|W(f)|^2 |T_{cs}(f)|^2 \right]^{1/2} \left[\phi_u(f) \quad f \Big|_{0.1}^{0.3} \right]^{1/2}$$

where W(f) is in 1/gz, $T_{cs}(f)$ is in $g^2/Ft/Sec^2/Hz$ and $\phi_u(f)$ in ft/sec

and Hz is .2

Then for Sea State 3

$$D_i = \left[4^2 \times .000408 \right]^{1/2} \left[(3.5) \quad .2 \right]^{1/2}$$

$$D_i = .0808 \times .8367 = .0676$$

which just exceeds the ride discomfort index for long term (over three hours) operation.

Peforming this same computation for all sea states the following vertical and lateral D_i are determined:

Sea State	Vertical D_i	Lateral D_i
3	.0676	.0338
5	.113	.0566
7	.134	.0669

Thus, for the assumed conditions, riding on the surface of the water does not exceed short term limits (0.28) at any Sea State and exceeds long term limits (0.10) vertically at sea states 5 and 7.

Remember that the weighting factors are those of MIL-F-9490D and that they have not been corrected for lateral sensitivity exceeding vertical sensitivity.

It is evident from this example that appropriate modifiction of MIL-F-9490D would provide a method of quantifying motion limits for sea based aircraft.